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The Greenhouse Effect and Biological Diversity

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THE CATASTROPHIC GLOBAL IMPACT of rainforest destruction on the species that inhabit tropical areas is now receiving increased attention in the media. In contrast, the slow but inexorable changes in climate that are a by-product of rainforest destruction have only recently entered the limelight. The accumulation of gases in the atmosphere due to the burning of fossil fuels and the reduced photosynthetic potential of a deforested Earth produce climatic effects that are likely to be profound.

In two papers that are destined to become citation classics[1,2], Robert Peters of the World Wildlife Fund made the logical connection between the current trends towards a warmer climate and the fact that the present sites of many nature reserves may soon no longer enjoy the meteorological conditions necessary for the well-being of the species they were established to support. A conference convened by the World Wildlife Fund, held in Washington in October 1988, brought together speakers from a variety of different disciplines to discuss the potential consequences for biodiversity of the currently available predictions for climate change. This article complements two other recent reports of the conference[3,4].

Predictions for climate change

The main cause of global warming is a build-up of carbon dioxide in the atmosphere, the 'greenhouse' effect. George Woodwell (Woods Hole Research Center) estimated that atmospheric CO_2 is currently increasing at a rate of 1–2% per annum. This will give a doubling by sometime in the middle of the next century (Tables 1 and 2). When these approximations are placed in a number of 'state of the art' climate models, Steve Schneider (National Center for Atmospheric Research) suggests that given high, medium or low estimates for each set of variables, then mean temperature increases will be of the order of 0.06°C per decade, 0.3°C per decade or 0.8°C per decade, respectively[6]. Thus by the time CO_2 levels have doubled, mean temperature will have increased by between 1 and 5°C (Fig. 1).

Although some ecologists might complain that the sample size is limited to one when dealing with global phenomena, Schneider points out that this problem recedes when we compare our planet with Mars and Venus, each of which has an atmosphere that keeps it warmer than is expected given its distance from the sun. Mars has a thin layer of CO_2 and is 1–5°C warmer than it 'should' be, while Venus has a thick CO_2 layer and is several hundred degrees warmer than it should be[7]. The Earth's present atmosphere keeps us about 33°C warmer than our distance from the sun would predict.

Schneider stresses two important points about the effects of the changes. First, the rate of climate change is unprecedented and is several orders of magnitude faster than previous climate changes, which have permitted animals and plants sufficient time to evolve adaptations to survive an altered climate. Second, the major impact will not come from average changes in the weather, but from extreme events. For example, the probability of a July heatwave (>5 days at >°C) in Washington DC will rise from 17% to 47%, if average temperature goes up by 3°C. The probability of drought in the American Midwest, such as the one last summer which reduced grain crops by 20–40%, is also expected to increase. Similarly, although most models predict increased rainfall in the Indian subcontinent, which would ultimately be beneficial, if the increase leads to more flooding, India and Bangladesh will be subjected to further catastrophes during the transition period.

Tom Lovejoy (Smithsonian Institute) pointed out that around 20% of the excess carbon in the atmosphere comes from fires in the Amazon. Recently instituted satellite monitoring showed 178 000 Amazonian fires of more than 1 km² – far more than Brazilian authorities expected. A 50% reduction in present levels of atmospheric CO_2 would require complete cessation of rainforest destruction, as well as planting 2 million km² of forest. Norman Myers estimated that the cost of planting this many trees is of the order of $100 billion, or $10 billion per year for ten years. Not only would this area of new forest store around 1 billion tons of atmospheric carbon per year, but its cost is significantly less than the cost of the 'inevitable crisis management' budget that will occur when local municipalities demand relief from natural disasters. For example, the cost of building sea walls on the coastal United States will be of the order of $111 billion[8]; when combined with the loss of productivity in agriculture, this will make the cost of tree planting look small by comparison.

George Woodwell quoted Garret Hardin's criticism of industrial philosophy – 'focus profits and diffuse costs' – to support his arguments that we have begun to exceed earth's ability to withstand unlimited perturbation. The model of an environment of limitless resilience rules the current neoconservative economic view. However, this model just is not realistic. The earth is a finite living system which may no longer be large enough to accommodate the assaults of a rapidly expanding contemporary civilization. At present we are moving from a benign world of fairly predictable effects over the last 10 000 years, to a world where the only guarantee is that there will be more unpredicted surprises, like the Antarctic ozone hole. Economic policies need to be stretched to account for the buffering capacity of the environment, rather than the (relatively) trivial movements of profit or foreign exchange.

Woodwell also worried about the artificially high standards of objectivity and proof required by scientists involved with either government inquiries into environmental pollution or matters of public welfare that may affect the profits from a major industrial concern. Similarly, the cautious skepticism usually shown by scientists when developing knowledge tends to confuse the public when used to discuss the manifestations of 'un-natural' phenomena and may explain why scientists are such bad lobbyists – a complaint that was raised by several Members of Congress attending the conference.

Effects of climate change in terrestrial environments

Perhaps the most striking feature of many of the talks at the conference was the wealth of detailed knowledge released by persuading workers from a variety of different areas to ask themselves the question 'What will happen if the system I work on suddenly gets several degrees warmer?' Changes in climate are likely to have both direct and indirect effects on both animal and

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plant species. Although dramatic, the direct effects of these changes are relatively easy to predict. The indirect effects are often subtle, insidious and long lasting. A one degree increase in temperature is equivalent to a 60–100 mile change in latitude. Thus, many species of animals and plants are going to have to start dispersing. A rise in sea level from the melting of polar ice will particularly affect those living in coastal areas.

Thompson Webb (Brown University) presented graphs of average temperature over the last million years and the last 100 million years in North America derived, respectively, from pollen analyses and changes in oxygen isotopes of foraminifera. It is clear that the succession of ice ages have involved global temperature changes of about 5°C between glacials and interglacials. At the height of the last glacial, North America was 5°C colder than now. However, the whole evolution of *Homo* has taken place with climates at present levels or *colder*. To find a precedent for global climate 3–5°C *warmer*, we must look back about 20 million years, to a time when our ancestors were Miocene apes.

Effects on vegetation

Margaret Davis (University of Minnesota) analysed the geographical distribution patterns and dispersal rates of North American trees. Although it is possible to do experiments on the sensitivity of early life stages of trees to climate, we do not know the climate thresholds of adult trees. Experiments to determine these thresholds are constrained by the development time of the trees. Many tree species are so long-lived that we have insufficient time to undertake the provenance studies necessary to determine how their adult stages will cope with a completely altered environment.

Davis showed that spruce had managed to migrate at a rate of 200 km per century 9000 years ago, but this was achieved with northerly winds and northward flowing rivers. Most of the known ranges of other tree species expanded at rates of 10–40 km per century. The shifts required by a doubling of atmospheric CO_2 are of the order of 500 km per century, considerably faster than any of these estimates. As Michael Soulé (University of Michigan) pointed out in his concluding remarks, if a two degree increase in mean temperature over the next 50 years corresponds to an approximately 200 mile shift in the boundaries of a species range, then dispersal rates of the order of one metre an hour are required if species are to remain extant in areas with an equitable climate. This is several orders of magnitude too fast for most plant species. Moreover, although some plant species may be able to migrate at rates comparable to those of their optimum climates, the mineral properties of the soils they are presently adapted to might not be present in the same regions as their climatic requirements.

Boyd Strain (Duke University) illustrated that the reproductive strategies of many plant species are altered as levels of CO_2 increase; *Desmodium paniculum* produces increased numbers of both tillers and seeds under increased CO_2 regimes. Similarly the present limiting effects of nutrient supply could be overcome for most plant growth parameters by an increase in atmospheric CO_2. This affects not only the composition of future plant communities, but may also affect our ability to reconstruct past ones using pollen data!

Thompson Webb reinforced this expectation of changes in community structure, rather than uniform displacement of collections of species. Pollen analyses have shown that 18 000 years ago spruce grew in association with a variety of sedges in the open parkland of the American Midwest; by 10 000 years ago, spruce formed a closed canopy forest in southern Canada. The present boreal forest association of spruce and birch in this region is no more than 6000 years old. Therefore, as temperature changes we should expect not only transitional dislocation, but whole new ecological communities to form. Russell Graham (Illinois State Museum) made the same point with regard to mammalian faunas. He also linked the extinction of much of the Canadian–Alaskan megafauna 10–20 million years ago to the loss of sedge and other 'candy-bar' fodder species as well as the closing of the forest.

Both Dwight Billings (Duke University) and Ian Woodward (Cambridge University) suggested that the arctic tundra may completely disappear as a habitat. About 27% of the earth's soil carbon is stored in arctic tundra (14%) and in the boreal forest or taiga (13%). If the upper 2–3 m of permafrost which binds the tundra together is lost, the wet coastal tundra will also be lost. J.P. Myers (National Audubon Society) showed that this would have a disastrous effect on the populations of migratory birds and mammals that utilize this habitat as a breeding area.

Table 1. Carbon stocks and flows[a]

	Billion tons C
Stocks:	
Atmosphere	750
Vegetation and soil	2000
Flows (per annum):	
Photosynthesis	−100
Respiration	+100
Fossil fuels	+5.6
Deforestation	+1–3
Annual accumulation in atmosphere[b]	+3.0

[a]1980 figures, from the presentation by George Woodwell (with permission).
[b]Most of the remaining accumulation is oceanic.

Curiously, there may be a few crumbs of optimism. Boyd Strain showed that increased CO_2 levels alone have a promoting effect on plant productivity[9], and might, for instance, lead to 40% more wheat seed in a doubled CO_2 atmosphere. Radishes mature in 12 days instead of 20 in a tripled CO_2 atmosphere. These changes could benefit both third-world farmers and natural ecosystems, where increased plant growth could even lead to some buffering of atmospheric CO_2 increase. However, climatic changes are likely to be more important than increased growth, as levels of increased productivity are unlikely to compensate for the disruption of both agricultural strains and natural habitats.

Effects on animal communities

Dennis Murphy and Stuart Weiss (Stanford University) pointed out that in mountainous areas species

Table 2. Carbon emissions from industrial sources (1985) and deforestation (1980), in millions of tons[a]

Country	Industry	Deforestation
United States	1186	
Soviet Union	958	
China	508	
Brazil		336
Japan	244	
Indonesia		192
West Germany	181	
United Kingdom	148	
Colombia		123
Poland	120	
France	107	
Cote d'Ivoire		101
Italy	101	
Thailand		95
East Germany	89	
Laos	85	
Nigeria		60
Philippines		57
Burma		51
Others	~2000	~560

[a]Figures from Ref. 5.

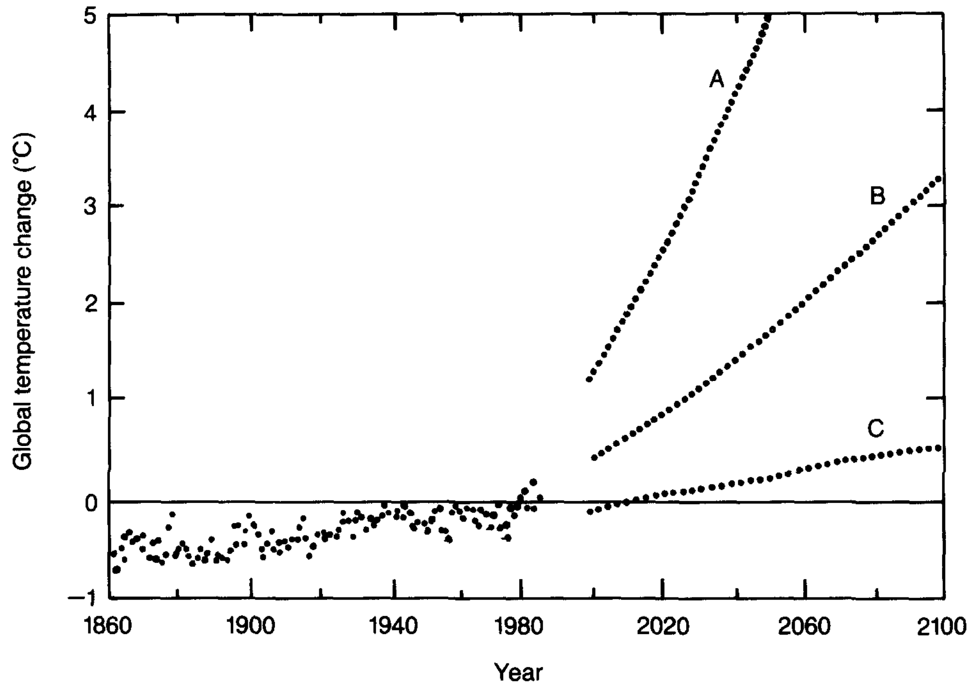

Fig. 1. Three potential trace gas scenarios used for simulations of future climate change. The scenarios attempt to account for a wide range of uncertainties encompassing climatic sensitivity to greenhouse forcing and thermal lags due to oceanic capacity. Scenario A: continued growth of emissions at rates that are compounded annually, giving a rate of temperature change of 0.8°C per decade. Scenario B: fixed annual growth of greenhouse forcing, giving a rate of 0.3°C per decade; if the human population continues to grow, this scenario assumes a decrease in per capita emissions. Scenario C: drastic curbing of CO_2 output (possibly half present fuel use), giving a rate of 0.06°C per decade; greenhouse forcing ceases to increase after year 2000. *Redrawn from Ref. 6.*

may respond to climate changes by migrating vertically over relatively short distances; boreal habitats may only have to ascend around 500 m to compensate for a three degree temperature rise. However, migration to higher altitudes leads to a concomitant reduction in the total area of any habitat type, so species with larger area requirements may go extinct. Present estimates of species–area relationships for the fauna of boreal 'habitat islands' of the Great Basin mountain ranges suggest that 10–50% of currently extant species may go extinct following a two degree increase in temperature in the next 50 years.

Gary Hartshorn (Tropical Science Center, Costa Rica) talked about the effects of global warming on tropical forest biodiversity, and suggested that although changes in total rainfall might not be critical for undisturbed forests, changes in the temporal patterns of rain would be catastrophic for many species of insects, birds and mammals. If no rain falls in the wet season, or rains occur in the dry season, then this will disrupt the flowering or fruiting patterns of many plant species. Since many animal species have breeding systems that are finely tuned to these patterns of resource renewal, changes in their temporal frequency could lead to the disruption of breeding systems, and this could further increase present extinction rates in tropical forests. Loss of the species that act as pollinators and seed dispersers would then ultimately lead to the loss of the dependent plant species.

Effects of climate change in aquatic environments

Having pointed out that coastal marine ecosystems constitute around 8% of the world's surface, Carleton Ray (University of Virginia) described how exquisitely well-tuned marine organisms are to maintain themselves in a region of constant temperature. Shad on the eastern seaboard of the United States migrate to maintain themselves at a constant temperature of 18°C. This entails a northerly migration in populations from the southern part of the range and a southern migration by fish in the north. Since the proximate cue for this migration seems to be change in day length, a change in water temperature may disengage the signal from the context in which this has evolved.

Moreover, changes in life histories could result as populations from different ends of the species range have different life history strategies. Shad in Florida presently breed once exhaustively, whereas those further north in Canada delay their onset of sexual maturity and breed sparingly over many years. These differences arise because the chances of juvenile survival are high in Florida, but more limited in the north where the harsher, more variable climate makes life in the rivers more risky. As warming occurs both the harshness and the variability of the climate might be reduced and foster a more 'Floridian' life style. These life history changes could have a profound impact on the fisheries that exploit this species.

Increased sea levels due to polar melting

Some of the largest proportional increases in temperature are likely to occur in arctic and subarctic regions. Under some scenarios this would lead to the possibility of an ice-free Arctic. Melting of the polar ice cap could also have disastrous consequences for many of the world's major fisheries, which are concentrated at the boundaries of arctic–subarctic oceans. Primary productivity in these areas is very much dependent upon the production and annual melting of the ice-edge.

Vera Alexander (University of Alaska) described how the edge of the ice barrier is crucial in refracting and concentrating the sun's very oblique rays in northern latitudes. This creates a massive annual phytoplankton bloom that grows on the underside of the ice-edge and supplies a substantial portion of the energy input in some arctic areas. The extreme cold and strong salinity gradients around this ice-edge restrict the growth rate of populations of aquatic invertebrates able to exploit this resource, so much of it ends in the benthos. Here it is harvested by a variety of squid and other benthic mollusks, which are in turn exploited by guilds of diving vertebrates such as walruses, seals and birds.

Because the predicted levels of warming are substantially higher in polar regions, perhaps as much as 5°C, and proportionally biased towards winter, then it seems likely that areas that now exhibit a seasonal ice cover may become ice-free, while the edge of permanent ice will retract and, due to the decreased albedo of the arctic region, may even disappear. This reduction in the length of the productive edge region will considerably lower rates of primary production in this region with resultant catastrophic consequences for the marine birds and mammals that rely on this resource.

A direct consequence of this melting of the polar ice caps would be a significant global increase in sea levels, by perhaps as much as 2–3 m. Carleton Ray also discussed how this might affect different species of corals that grow in shallow coastal waters. An initial analysis suggests that fast growing species such as

Agriporas would be able to cope. However, changes in temperature differentials between different regions suggest that the frequency of tropical storms may increase; this would be disadvantageous to the branching elkhorn and staghorn corals which are very susceptible to storm damage. Under these circumstances slower growing species such as brain corals might do better. As corals with different growth forms offer different degrees of habitat complexity, any diminution of structural diversity will inevitably reduce species diversity of both the fish and crustacean communities.

Florida may already be exhibiting the effects of global warming and sea-level rises. Attempts to determine the site of Columbus's landing to celebrate the quincentennial of his arrival have been frustrated by the fact that the site is now offshore. Larry Harris (University of Florida) discussed the problems of conservation in areas such as the Everglades National Park which, because of its low-lying topography, decreases by 50 km for every metre of mean sea-level rise. Even if the vegetation can grow fast enough to persist, it and its associated animals will be trapped between a rising sea and large human settlements living inland. The principal source of mortality for many of Florida's endangered species (key deer, Florida panther and manatee) are collisions with vehicles and vessels; this mortality increases as their populations become squeezed into smaller areas bounded by either the sea or human populations. Both Harris and Robert Peters emphasized the crucial importance of setting aside land for 'corridor' reserves along which species can migrate in response to climatic change.

Research needs

Although many of the contributors called for increased financial resources to set up basic monitoring facilities, it is important that this monitoring be tied in with the collection of meteorological data, and that both weather data and ecological data be collected on a variety of different scales. For example, it will be important to be able to link studies of the effects of climate change at the level of individual leaves to those of whole plants; from these we should be able to examine effects within plant populations and simple communities, and from this it should be possible to say something useful about whole watersheds.

The problems of scale here affect not only the ecological variables, but also weather variables. It is important to remember that the weather measured at a standard weather gauge 1 m above the ground is more similar to the weather measured in the same way 100 km away, than it is to that on the soil surface immediately below either weather station!

While mathematical models will be invaluable in determining how best to structure data collection, such studies are going to require greater flexibility in research institutes to facilitate interdisciplinary research. Nevertheless, the benefits gained from examining systems from a variety of novel perspectives are likely to enhance considerably our basic knowledge of how ecological processes operate and thus how they will respond to climate change.

From the pure research perspective, large-scale increases in temperature represent a massive selection experiment. Punctuated equilibria, saltational events and continuous selection can now be monitored for almost any extant organism. Studies that focus on the boundaries between specific biomes and on particular communities of economic importance are those that are most likely to produce the most immediate results.

Policy needs

The conference's concluding session underscored the need to stop rainforest destruction. Loss of rain forests have contributed to between 20 and 30% of the current CO_2 build-up. Further loss of forests will only lead to a more rapid accumulation of CO_2 in the atmosphere. Indeed as Norman Myers emphasized, the synergistic interactions between CO_2 levels and forest destruction suggests we should very rapidly begin to start planting new forests. It may be time to hang the chain-saw in the hall and study soil once more.

This point was reinforced by Jerry Franklin (US Forest Service, University of Washington), who foresees catastrophic disruption of old-growth douglas fir in Oregon and Washington if either severe storms or wildfire increase in frequency. He argues for changing forest service policy to maintain more forest on longer cutting cycles, because 'the war for biodiversity will be won or lost on semi-natural landscape'. His picture of the new ecologist is a woman with a shovel and a backpack full of seedlings.

But replanting can only be a palliative measure. What this conference must do is provoke a new activism: on the small scale for being able and willing to protect forest animals and plants, and on the large scale for planting, ceasing to cut down trees, and even demanding more efficient industry. Daniel Botkin (University of California, Santa Barbara), author of the JABOWA computer model most widely used for forestry predictions, did not talk mainly of computer modelling. He talked of how to save the tiny, endangered Kirtland's warbler, which only nests in a few sandy-soiled jackpine stands in Minnesota, and how to manage the million acre Boundary Canoe Area, which will probably change from its present boreal cedar forest into deciduous woods full of sugar maple.

Global warming will not only affect biodiversity, but will also affect issues closer to the hearts (and wallets) of the world's least endangered species. Indeed many of the predictions suggest scenes more reminiscent of science fiction (Anthony Burgess's *End of the World News*[10] seems uncanny in this respect). Although increased levels of CO_2 may enhance plant productivity, a hotter climate will considerably reduce agricultural production in many areas (further increasing pressure on remaining wildlands). Diseases at present confined to the tropics may establish in more temperate regions.

Perhaps most frighteningly for *Homo corporatensis*, increased sea levels are going to do unpleasant things to the value of real estate, particularly in the coastal regions where a third of the world's human population lives. This means that politicians are talking about global warming, and in Washington and elsewhere talk means votes. So far, mapping the human genome has not been an electoral issue; in contrast, environmental issues have appeared as skeletons in the closets of both candidates in the recent US presidential election. A rational bureaucracy should begin to think about putting its money where its votes are, so ultimately talk may mean money. Whereas the net benefits from the human genome project can only be speculated about, the losses that will be incurred from low levels of funding for environmental issues are potentially enormous. As congresswoman Claudine Schneider (Rhode Island) emphasized, the environment is ultimately a National Security issue. The United States is responsible for the largest share of added global CO_2 (Table 1), and also has the greatest financial interest in approaching Japanese standards of energy efficiency. Schneider's current bill before congress (H.R.5460 The Global Warming Prevention Act) continually emphasizes the economic value of competitively increasing energy efficiency in industry in order to provide the incentives necessary to reduce rates of CO_2 build-up. Energy consumption levels in the United States have now returned to pre-oil embargo levels. It makes sound economic sense for the USA to develop adaptive long-term environmental strategies that cut down on both the causes and the consequences of global warming.

On an international scale, the magnitude of the problem would seem to require a Breton Woods style meeting of leading politicians, economists, scientists and wilderness managers. Essentially, all the world's nations need to set and maintain international standards for environmental management. The global warming issue is as serious as those that were addressed by the economists of 1946 when faced with major international imbalances in the import and export abilities of different nations. Indeed the imbalances of CO_2 production and fixation between different nations and the fact that too large a build-up effects everyone on earth, demands that long-term plans for economic development should incorporate international legislation for CO_2 management. Ultimately, fluctuations in levels of CO_2 will have greater effects on the planet than more short-term fluctuations in exchange rates.

The recent success of the Montreal protocol in coming to grips with the problem of stratospheric ozone depletion offers some hope. Not because it provides for a solution, but because it shows that scientists, diplomats, industrialists and politicians can work together and produce a set of rules that are modifiable as more information accumulates. This acknowledgement that dynamics matter if assessment is to be used to generate effective policies is the key to future progress in the rational management of planet Earth. A two degree increase in temperature over the next 50 years will significantly reduce the quality of life of everyone now alive on this planet and all their offspring. Do we really want to be known as the generations who allowed their children to burn?

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